16.810 **IAP 2007**

Engineering Design and Rapid Prototyping

January 28, 2007
Version 1.3

Deliverable C

CAD Model and Performance Analysis

System: MIT Space Elevator Team Beamed Ribbon Climber

Component or Subsystem: Microwave Beaming System

Team Name: The Rather-Naïve-About-Optics Team

Team Member 1: Ethan Huwe

Team Member 2: Arka P. Dhar

Team Member 3: Chris Mandy

1. Electromagnetic Wave Circuit

This section deals with models of the trajectory of the microwaves from their source to the climber. Field modeling was performed using Comsol 3.3 acquired with a 14-day trial student license graciously provided by Comsol Multiphysics.

Pre-Optimization decisions:

As the number of constraints on the system were rather limited, the number of options for our design was large enough that we couldn't address all possibilities within the time available. We chose for instance not to attempt to emit the electromagnetic radiation through helicoidal antennae simply because we didn't have the necessary knowledge or the time to acquire it. Instead our system relies on magnetrons to emit electromagnetic radiation. We also chose not to transmit the radiation through coaxial cables as it would require two conversions, radiation to electricity out of the magnetron, and electricity to radiation on the emitting side of the beam, and we don't have the knowledge to design this in a meaningfully efficient way.

We have omitted from the CAD model of our design both the wave combiners and the polarizing scheme. This is mainly due to our unfamiliarity with Comsol and the large amount of work needed to add such intricate items with numerous boundaries. To achieve sufficiently powerful emitted radiation, 12 magnetrons would have to be assembled with beam combiners (WR-187 TE-1 4-port directional couplers) in two sets of 6, then connected to a WR-187 TE-1 single box quadrature branch line coupler, combining the two beams into one with a 90 degree phase difference, achieving polarized light. It is this beam which we have set as boundary condition for our CAD model in Comsol. Other possibilities for polarization include Fresnel or Moony rhombs and quarter-wave plate. Since quadrature branch line couplers seem to have poser losses on the order of 4%, we decided we wouldn't be able to achieve such a value by designing our own optical crystal and opted for buying couplers.

Optimization:

As waveguides of a similar price can be obtained for any frequency and power range, and since achieving the required output (in our CAD model) resulted in similar costs in magnetrons, we've chosen to keep the specification of the one magnetron the MITSET team already has, and propagate 5.801GHz (wavelength of 5.17 cm) microwave radiation.
The optimal standard waveguide size for this frequency is the WR-187 standard ('G Band') which has dimensions 1.872''x0.872'' (units always in inches for some reason) and a range of 3.93GHz to 5.85GHz.
The microwave emitting horn was designed using Paul Wade's mysteriously named Hdl_3b4 program, resulting in the following dimensions:

- Axial length: 64.6mm
- H-plane aperture: 135.9mm
- E-plane aperture:100.6mm
- Uncorrected Horn Gain: 15.8 dBi
- H-Plane Phase Centre: 1.41λ
- E-Plane Phase Centre: 1.31λ

This horn had highest power flux, considering its interaction with the parabolic dish: decreasing the gain will result in a less efficient horn, increasing it will result in a larger horn that causes a larger amount of radiation to be reflected off it after being reemitted by the parabolic dish, and resulting in a diminished net overall efficiency.
Modelling these in Comsol, we tweaked the input power, H-bend lengths in the wave guides to achieve the required power output of 127W/m^2 (to power 2m-diameter rectennae).
It was also found that adding a curved dielectric tubing behind the horn to guide the waves upwards increases the output power in a radius of 15 wavelengths around the horn by 30%. The shape of the curve does not significantly affect this value, so long as it is convex.
The final output efficiency is 8% according to Comsol. This means that our system emits a power flux of 130W/m^2 outside the parabolic dish. This value estimate is certainly not final (see section 3). Our initial back of the envelope calculation based on the link equation:

$$\frac{C}{P} = \frac{L_l G_h G_p L_a \eta_p \eta_h \pi D^2}{16H}$$

With C/P the Received to Emitted Power flux ratio, L_l the line loss, L_a the transmission power loss, G_p the parabolic antenna gain, G_h the horn antenna gain, η_p and η_h their respective efficiency, D the rectenna diameter and H the horn antenna footprint on the parabolic antenna; yields an efficiency of 14%.

2. Structural Support

a. Waveguides and Horn

At first we decided to have a variable height adjustable horn holding stand, so that if required we can adjust the height of the horn to achieve better microwave collimation at the rectenna plates on the climber. But then analyzing the situation, we came to the conclusion, that such a feature is not that important as we can achieve the best result only when the horn is hold at the focal point. The focal point of the parabolic dish was found to be around 40in above and 60in from the end of the antenna. It was challenging to make the stand stable, because whatever structure we use, one end always bent forward because of the unstable weight distribution. (Ref: CAD modeling of the stand)

Our remedy this problem was that to increase the height of the stand, so that even after it getting bent the horn will be hold at the focal point. Finally the dimensions that we got were Height (45in) and Length (63in). It proves to be pretty stable. More work can be done to improve the structural strength so that it can withstand wind produced vibrations etc.

3. Design notes

As the system is quite complex, we would like to add a few notes concerning further modeling of the system and testing, for the benefit of the MITSET team. Time constraints prevented the team from completing the following 4 steps we feel are absolutely necessary prior to purchasing any parts and testing:

- Thermal modeling and heat dissipation analysis.
  The software Comsol seems to provide appropriate tools for such an analysis, but a 3D model of the electromagnetic radiation path is necessary for accurate modeling to be performed. This is mainly due to the nature of the waveguides and horn which lack symmetry in the z-direction: the horn is "thicker than wide" in the z direction whereas the waveguides are "thinner than wide".
- The circularly polarizing section of the waveguide circuit should be added to the model, so that exact impedance matching can be achieved. This is crucial for the beaming system to be efficient
- The option of using helicoidal antennae should be analyzed sufficiently to determine whether or not their application could be more efficient
- Once these steps are taken, a specialist (Prof. Woskov? Mr. Willwerth?) should review the whole design to determine whether something obvious was overlooked.

In addition, since all references we have found agree that microwave circuits never perform according to design, we strongly recommend that testing be gradual rather than all-up. We propose to follow at least the following steps to validate the design:

1. Switch the magnetron(s) on (probably the hardest task listed here).
2. Assemble waveguide system up to horn (without horn, ie just the two H-bends). Roll a steel ball (with the aid of a permanent magnet) inside the waveguides and see how this affects performance. Insert screws where performance is enhanced by the presence of the ball.

3. Add Horn to the assembled circuit, and test performance. If the actual performance is excessively different from the predicted one, redesigning and building the horn with a greater gain is not particularly difficult, but will prevent a larger area of the radiation reflected by the dish from attaining the rectennas.
4. Use the magnetron's waveguide to directly project onto the parabolic dish and test for efficiency, reshaping the mesh in necessary areas.
5. Add the dish to the assembled circuit, and adjust the position of the horn until the focus is at the H-plane and E-plane phase centres are at the dish's focus (an offset of one centimeter can cause a 3dB loss).

4. References

- *The W1GHZ Online Microwave Antenna Book*, Paul Wade, 2006, http://www.w1ghz.org/antbook/contents.htm
- *Complete Wireless Design*, Cotter W. Sayre, McGraw-Hill, New York 2001, 547pp.
- *Microwaves: an Introduction to Microwave Theory and Techniques,* A.J. Baden Fuller, Pergamon Press, Oxford 1979, 326pp.
- *Microwave Principles and Systems,* Nigel P. Cook, Prentice-Hall, London 1986, 240pp.
- *Microwave Transmission,* J.C. Slater, Dover, New York 1942, 309pp.
- *Optics*, Arnold Sommerfeld, Academic Press, 1954, 383pp.
- *Comsol Multiphysics User Guide*
- *Comsol Multiphysics Radio Frequency Module User Guide, Reference* and *Model Library*

Standard Design

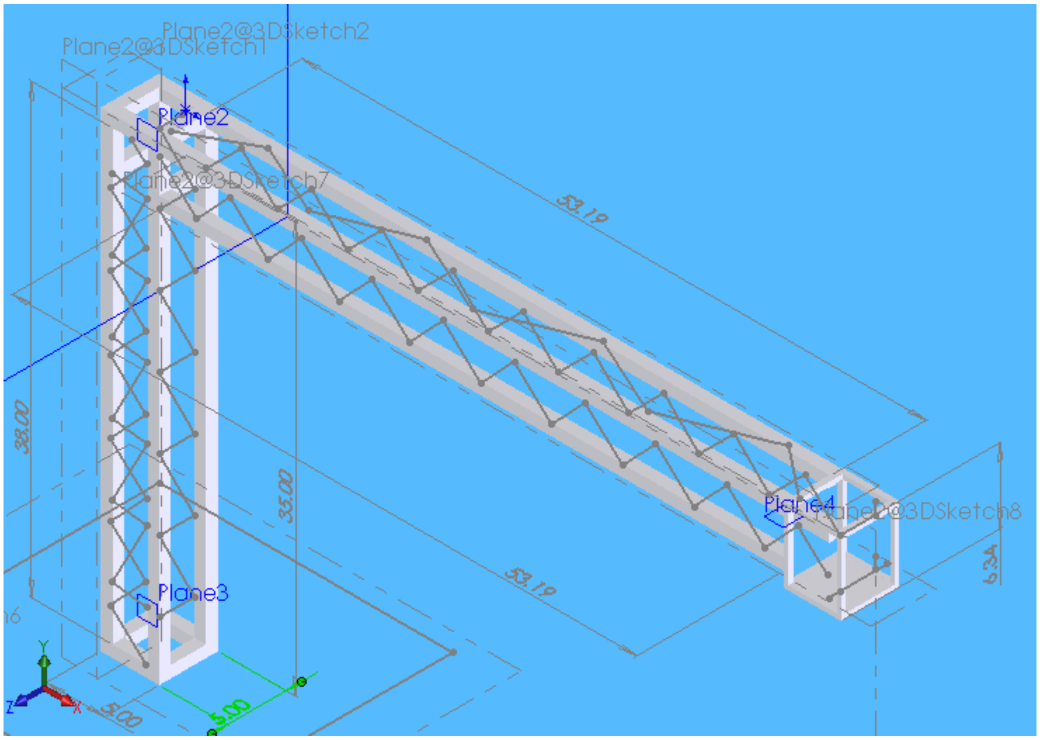


Figure 1. Stand CAD model and 2D FEM mesh.

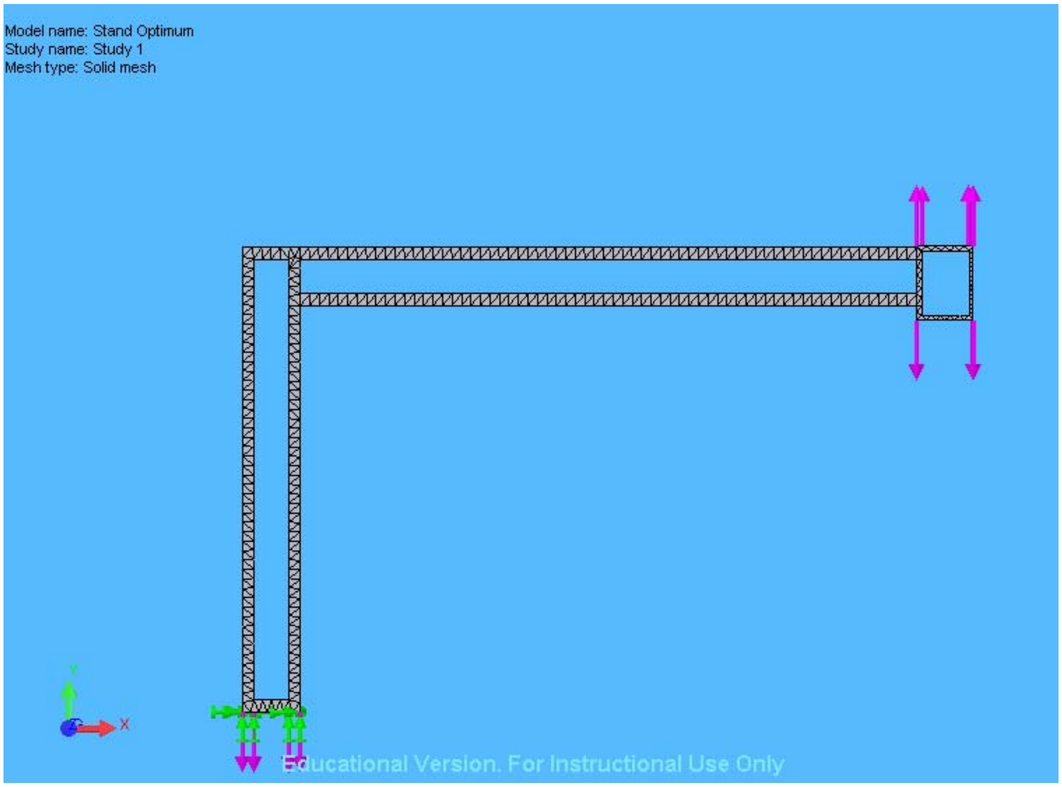


Figure 2: Von misses strain

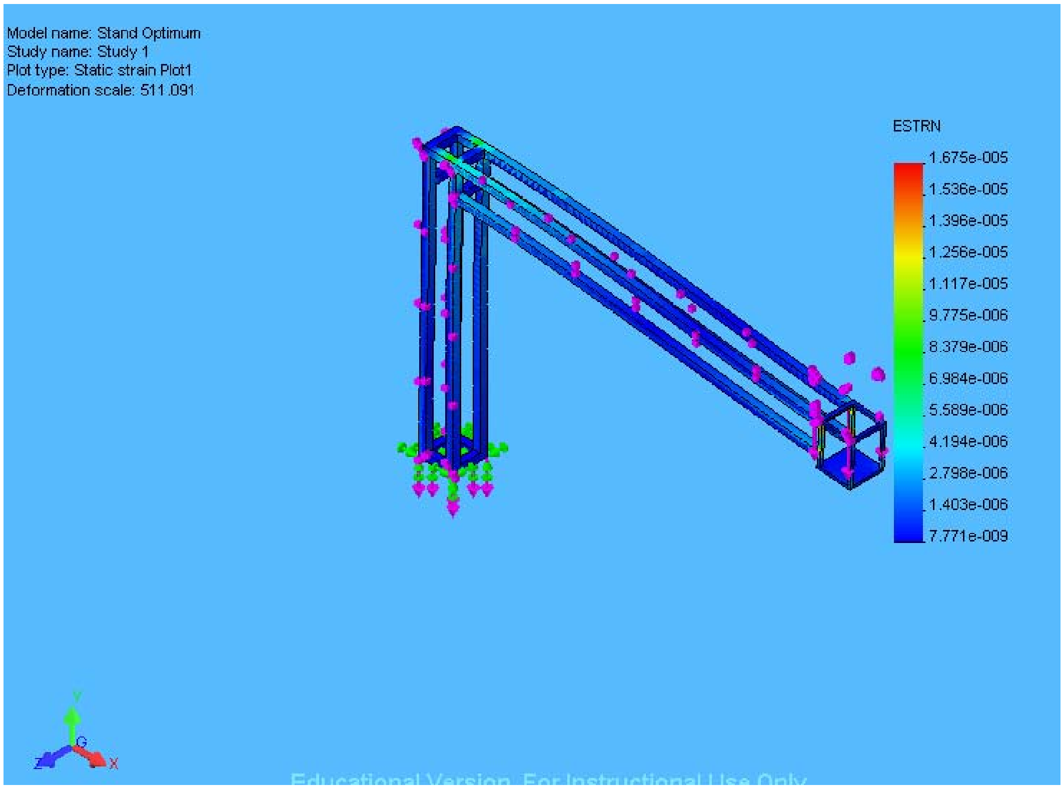


Figure 3: Stress

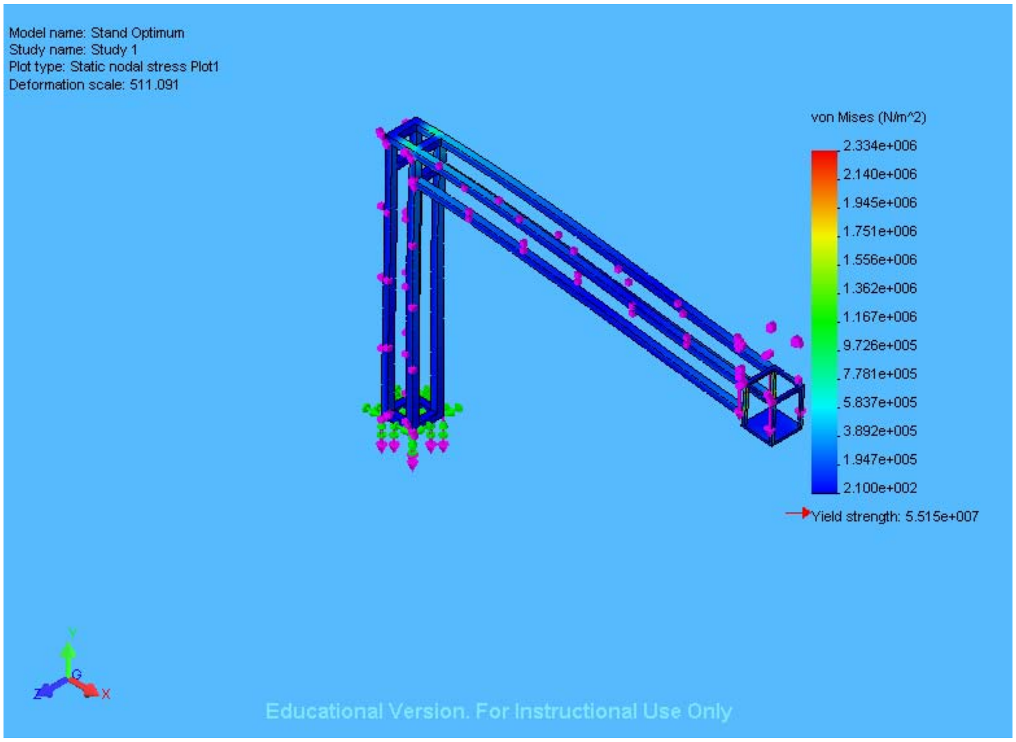
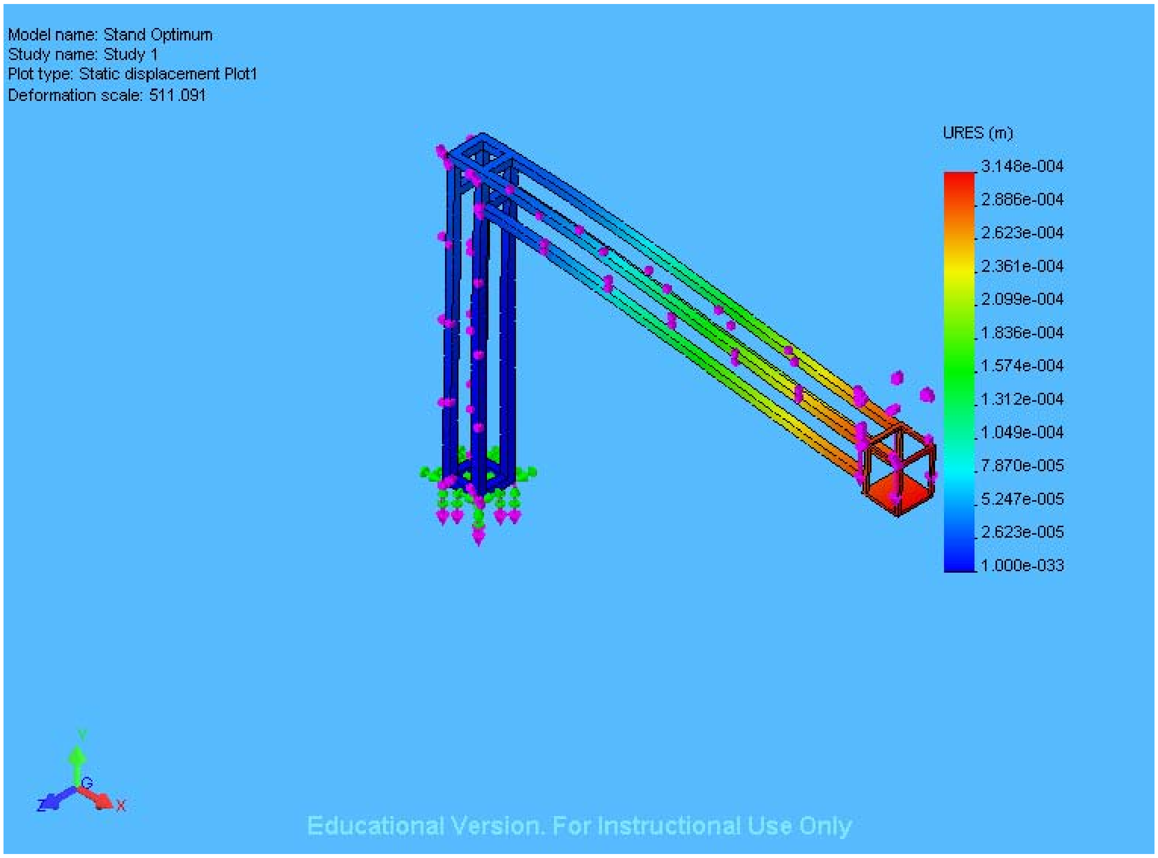
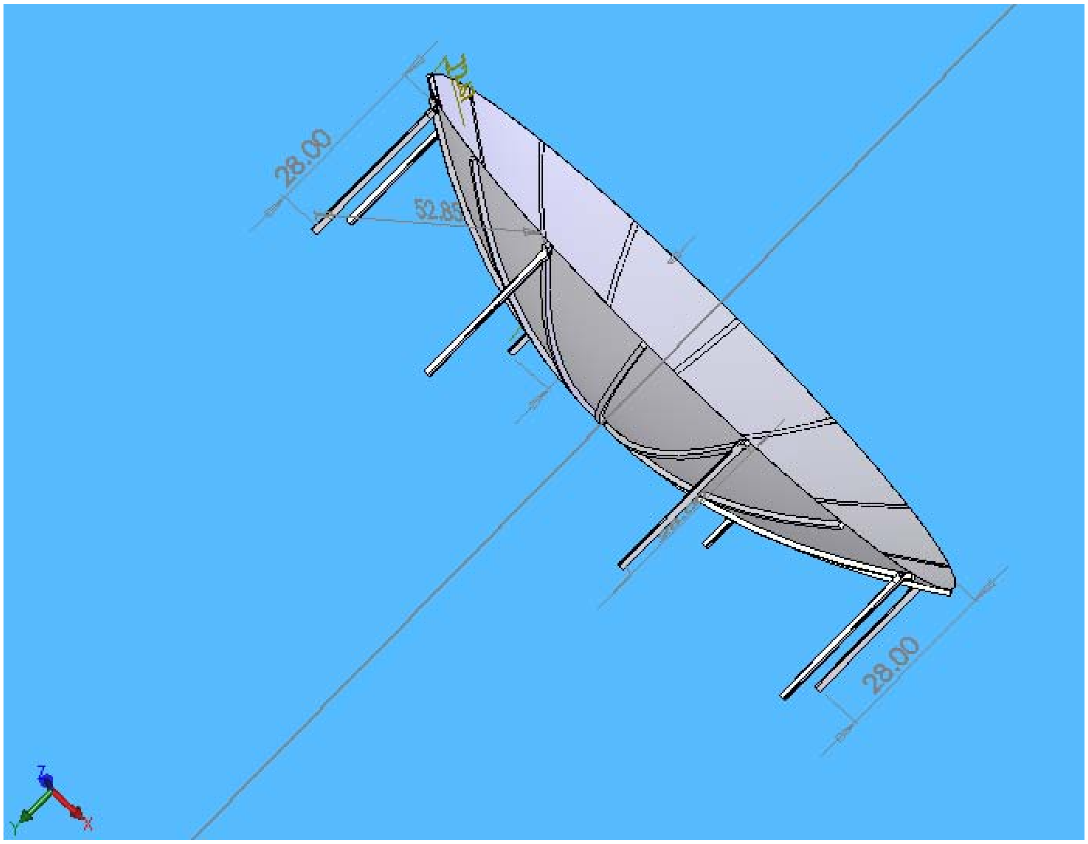
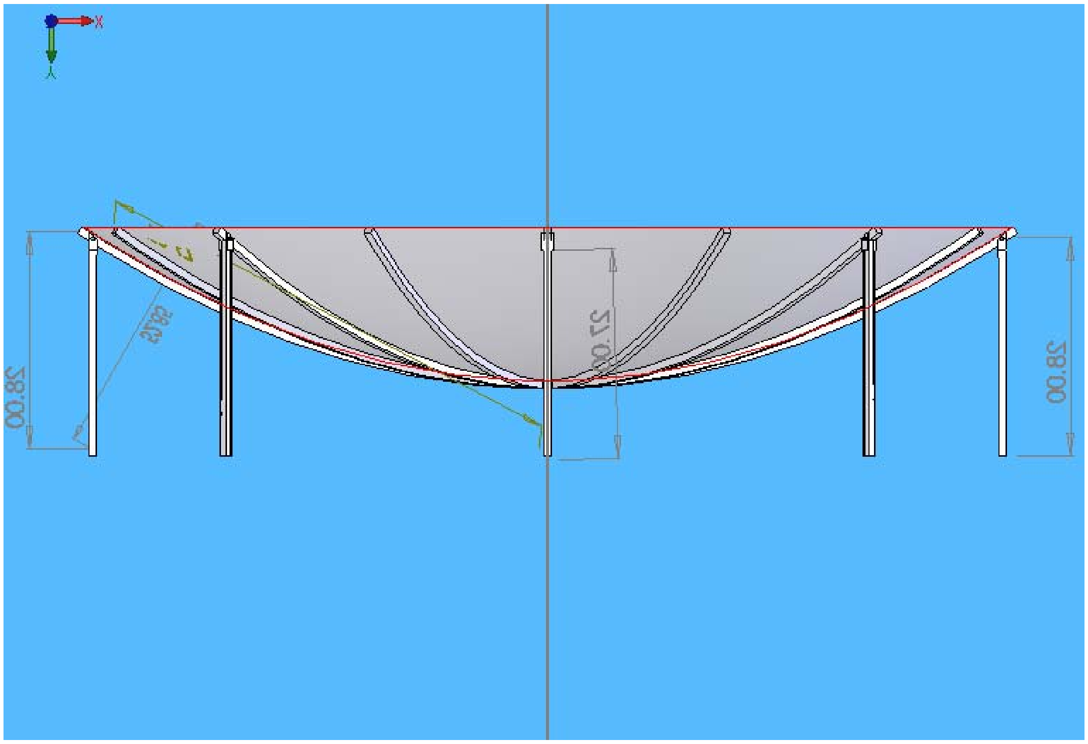


Figure 4: Displacement



CAD Model of the Parabolic dish.





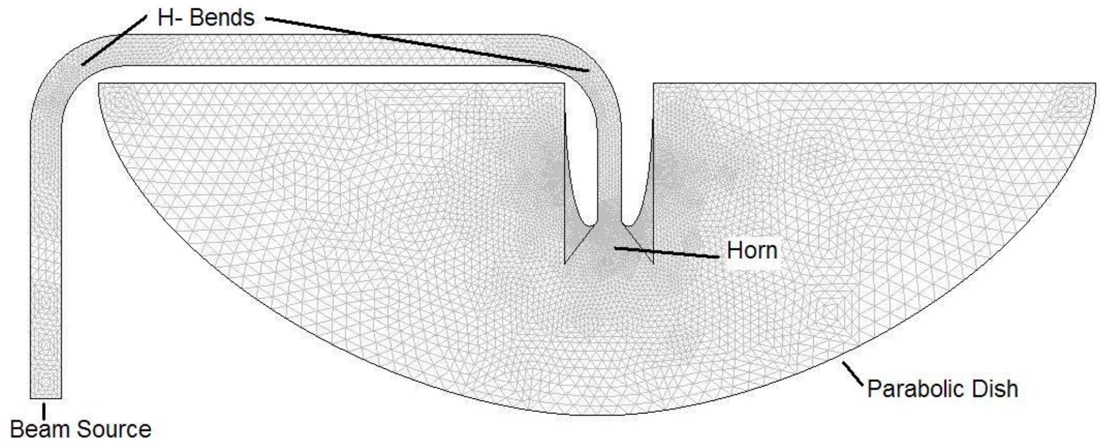


Figure 1. Microwave circuit CAD model and 2D FEM mesh.

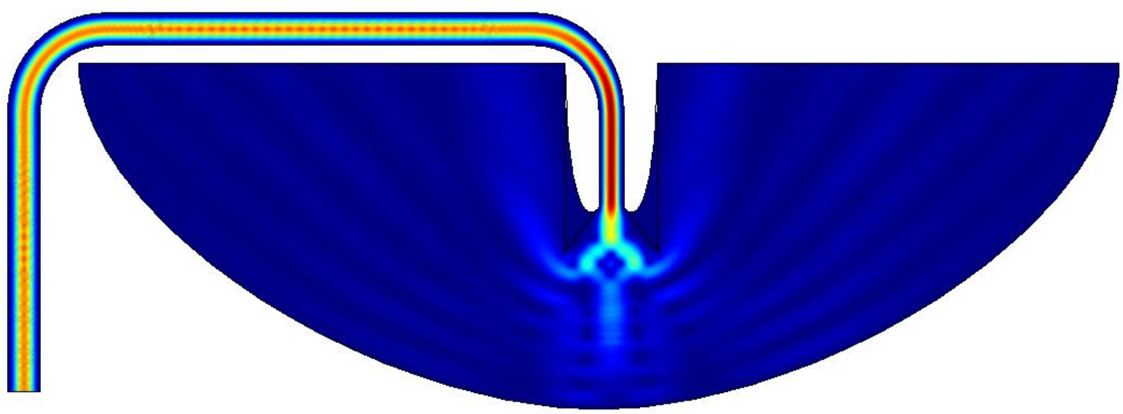


Figure 2. Power flux output plot. Dark blue corresponds to $130W/m^2$. $127W/m^2$ is required to furnish 400W to a 2m diameter rectenna.

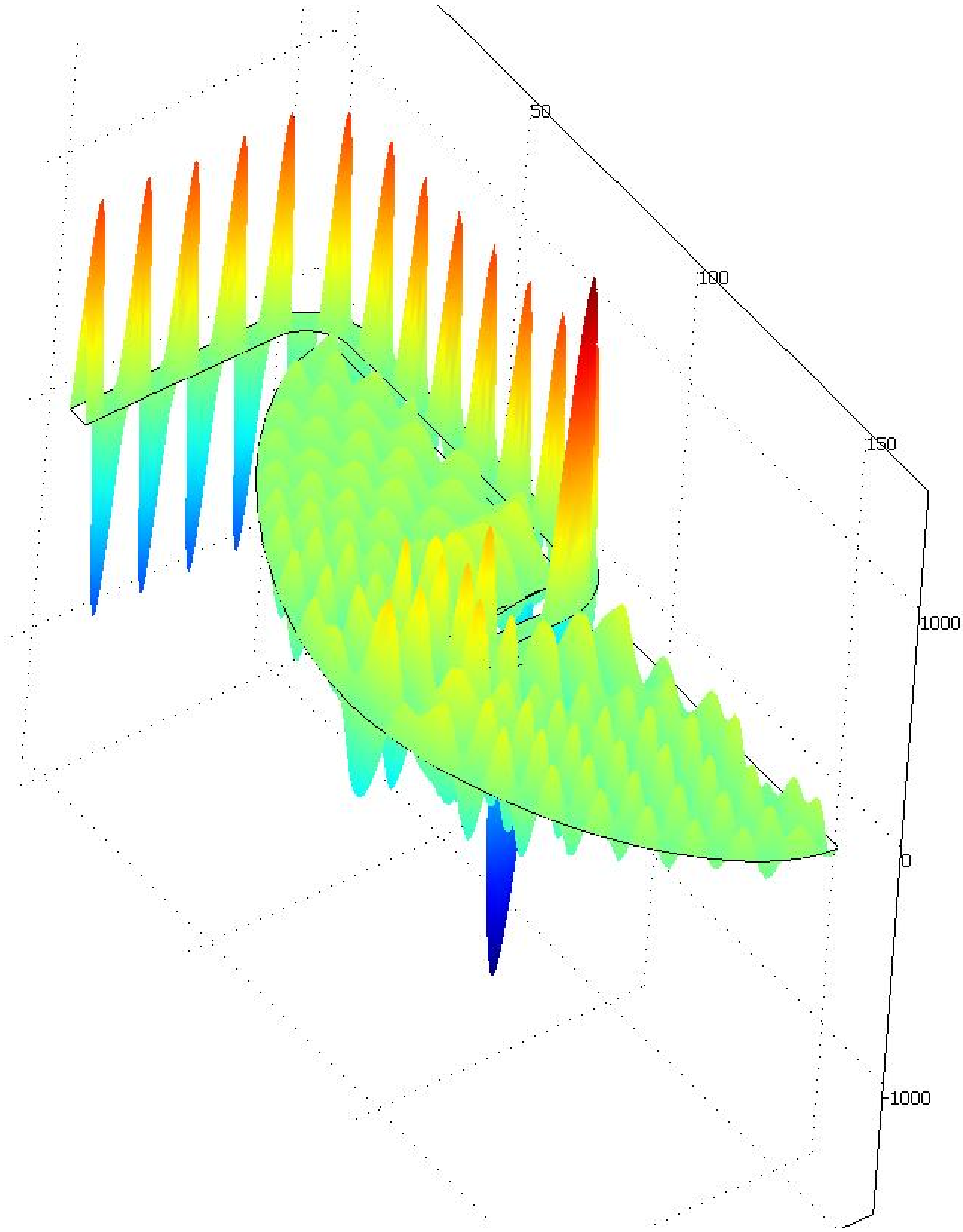


Figure 3. z-component of the Electric field of the microwaves inside the waveguides and antennae. The extremum peaks (red and blue) are 1300V/m and -1400V/m respectively.

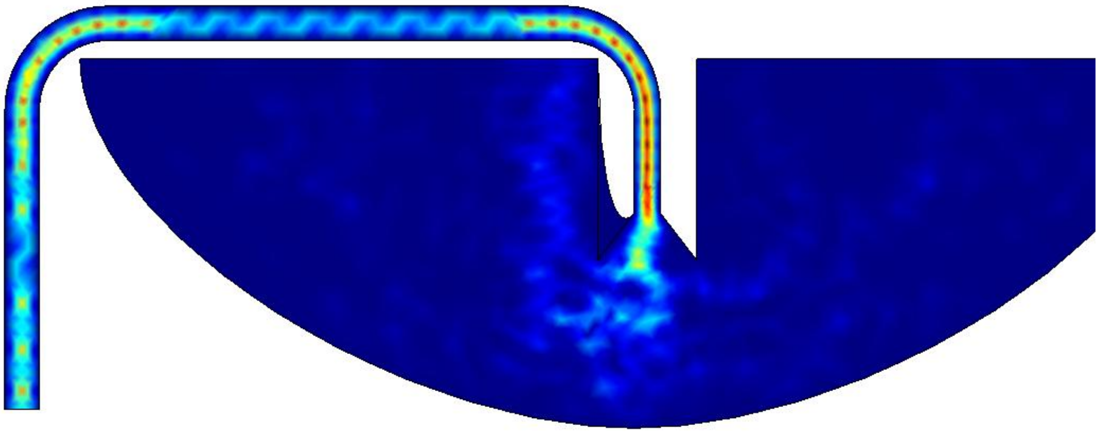


Figure 1. Adding a curved electric conductor outside the horn (left) increases the power output (lighter blue) at a distance of up to 15 wavelengths from the horn), as compared to not adding one (right).